Detection of Antineutrinos for Nonproliferation

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It is widely reported that India obtained its weapons-grade plutonium (Pu) by running its unsafeguarded CANDU reactors to produce Pu. In this project we have been examining the feasibility of monitoring the Pu content of reactor fuel from the antineutrinos emitted. When a uranium ^{235}U or ^{239}Pu nucleus undergoes fission, the unstable fission products beta-decay, thus emitting antineutrinos.

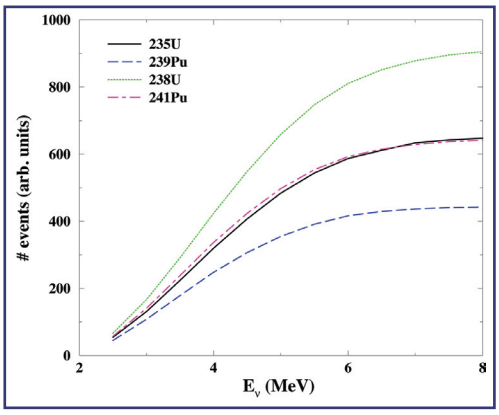

Figure 1—
The absolute magnitude of the detected antineutrino spectrum for ^{235}U is larger than for ^{239}Pu, so that the total number of antineutrinos detected changes with the relative fissioning fraction of the two isotopes in the reactor core.

On average, about five antineutrinos are emitted per fission. These antineutrinos are emitted over a period of up to minutes.

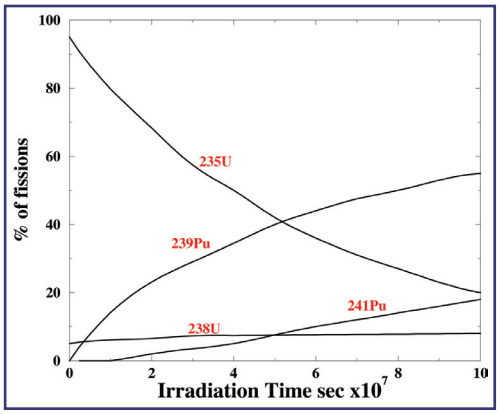

Figure 2—
The fission history for the 2.7% enriched (97.3% ^{238}U, 2.7% ^{235}U) reactor. As can be seen, the percentage of the total fission from ^{235}U steadily drops as a function of time, while that from ^{239}Pu steadily increases.

However, the fact that reactor monitoring is a steady-state measurement means that time variation is not an issue. The energy spectrum of the antineutrinos ranges from zero to about 15 MeV and peaks at about 3 MeV. However, only a very small fraction of the antineutrinos emitted have energies above 8 MeV. The differences in the fission products produced in the fissioning of U versus Pu leads to a significant difference in the magnitude and shape of the respective antineutrino spectra. These differences and the fact that the emitted antineutrinos cannot be shielded are key to the concept of monitoring the core fuel.

In the present work we restricted our studies to a Pressurized Water Reactor (PWR) similar to the San Onofrie reactor in California. We examine the predicted time-dependent antineutrino spectra for a 2.7%-enriched PRW reactor. To test the sensitivity of the expected signals to the initial U enrichment we also examined a 4.2%-enriched PRW.

A 3.4 GW power reactor emits on the order of 10^{26} antineutrinos per day. The absolute magnitude of the detected antineutrino spectrum for 2^{35}U is larger than for ^{239}Pu (Fig. 1), so that the total number of antineutrinos detected changes with the relative fissioning fraction of the two isotopes in the reactor core. Thus, for a fixed reactor power, the number of detected antineutrinos is a reflection of the core burn-up. The shape of the spectrum is also a measure of the core burn-up. As shown in Fig. 1, the cumulative number of antineutrinos (when folded over the detection cross section) as a function of antineutrino energy is different for the two species. By comparing the number of antineutrinos with energies up to 3 MeV with the number up to 6 MeV, pure ^{235}U and ^{239}Pu are easily distinguishable.

In Fig. 2 we show the fission history for the 2.7% enriched (97.3% ^{238}U, 2.7% ^{235}U) reactor. As can be seen, the percentage of the total fission from ^{235}U steadily drops as a function of time, while that from ^{239}Pu steadily increases. After about 3 years burning (30 GWd/MTU) the fuel has an isotopic composition of (95% ^{238}U, 1% ^{235}U, 1% ^{239}Pu, 3% high-level radioactive waste including ^{240,241}Pu).

A large pressurized light water reactor has about 240 fuel assemblies, of which 80 are replaced at the same time every year, and the assembled are then shuffled in their location. When the reactor is running in equilibrium, at the beginning of each fuel cycle one-third of the fuel is fresh enriched U, one-third has been irradiated for 1 year and one-third for 2 years. At the end of the cycle one-third of the fuel has been irradiated for 3 years and is removed and replaced with fresh fuel. Each fuel assembly typically contains one-half ton of fuel. Therefore, in 3 years about 5 kg of Pu will be produced in each assembly of normal fuel.

Typical diversion scenarios would likely involve the diversion of an entire fuel assembly and replacement with fresh fuel. In principle, a single assembly would contain enough plutonium to make a nuclear weapon. An unannounced removal of 1–2 additional fuel assembly at the same time that other scheduled work was being carried out would require an accuracy in the antineutrino detection rate of better than 1%. The detection of this type of change would be a much more difficult task than observing the 5% change in the magnitude of the spectrum over one fuel cycle.

In Fig. 3 we compare the expected time-dependent antineutrino count rate under normal operation of a 2.7% PWR with that expected for a significant fuel diversion. In this latter case we have assumed that an additional unannounced 10% of the fuel was replaced during a scheduled fuel cycle management. The solid curve shows the relative change in the number of events on normal fuel management, i.e., at the end of the fuel cycle the 3-year exposed fuel is removed and at the start of the next cycle the core consists of 1/3 fresh 2.7% U fuel, 1/3 fuel irradiated for 1 year, and 1/3 irradiated for 2 years. The dotted curve shows a realistic and significant violation of the nonproliferation treaty in which an additional unreported 10% of the 2-year irradiated fuel has been replaced with fresh fuel. In this case the start of the new cycle involves a core with 37% fresh 2.7% enriched U, 33% 1-year irradiated fuel, and 30% 2-year irradiated fuel.

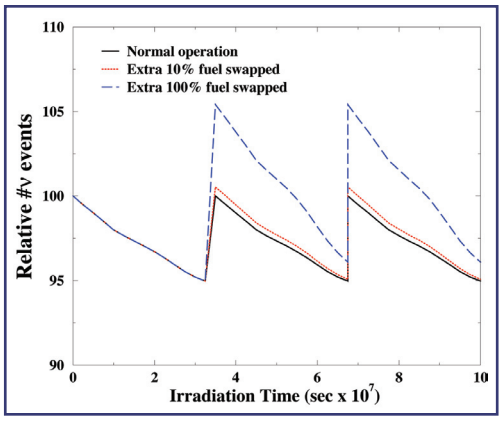

Figure 3— Comparison of the expected time-dependent antineutrino count rate under normal operation of a 2.7% PWR with that expected for a significant fuel diversion. The solid curve shows the relative change in the number of events on normal fuel management. The dotted curve shows a realistic and significant violation of the nonproliferation treaty in which an additional unreported 10% of the 2-year irradiated fuel has been replaced with fresh fuel.

In contrast to the above 10% diversion of the fuel scenario, gross diversions of fuel or gross deviations in the reactor operation from that announced would likely lead to quite detectable changes from the expected antineutrino spectrum. The long-dashed curve in Fig. 3 represents the expected number of antineutrino in the case that 2/3 (as opposed to the regular 1/3) of the irradiated fuel is replaced at the end of a 1-year cycle. In this scenario the start of the new cycle the core would consist of involves 2/3 fresh 2.7% U and 1/3 1-year irradiated fuel. This gross misuse of the reactor would lead to a 10% shift in the antineutrino count rate, to be compared with the 5% change expected under normal fuel-cycle management.

Thus, we conclude that antineutrino monitoring of reactors could be used to detect gross misuse of reactor for proliferation purposes. However, more subtle diversion of Pu, such as the diversion of a critical mass of Pu, would be very difficult.

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